Technology Advancement for Solar Sail Propulsion (SSP) for NASA Science Missions to the Inner Solar System

A Summary Status Briefing to the Solar Sail Technology & Applications Conference

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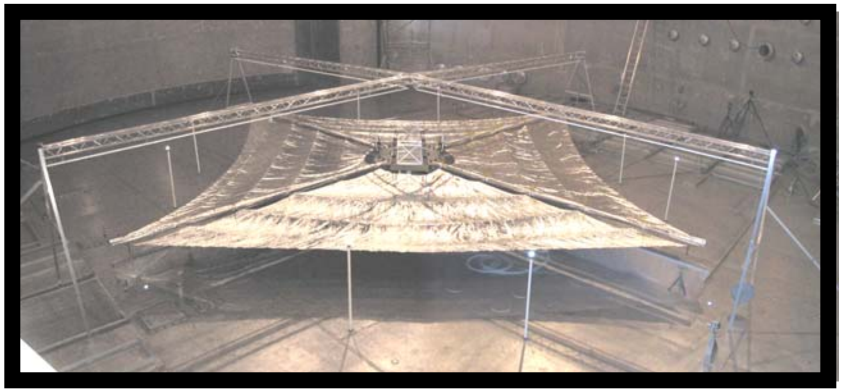
Contents

[Solar Sail Propulsion - SSP]

- Tech development roadmap
- Tasks funded to date
- TRL 6 Definition
- Future development plans



SSP Roadmap Foundations

- Requirements Flowdown
- SSP mission statement
- mission pull
- Technology Advisory Group
- ROSS NRA

Requirements Flowdown

FAD (10/31/01)

Level I – HQ/Science Mission Division

PCA (10/16/03)

Level II – HQ (MSFC)/In-Space Propulsion Program

TAG

ISTP Project Plan

Level III – MSFC/ Solar Sail Propulsion Technology Area

Contracts/TTAs

Level IV – Contracts & Tasks

SSP Roadmap

SSP Mission Statement (Draft Revision)

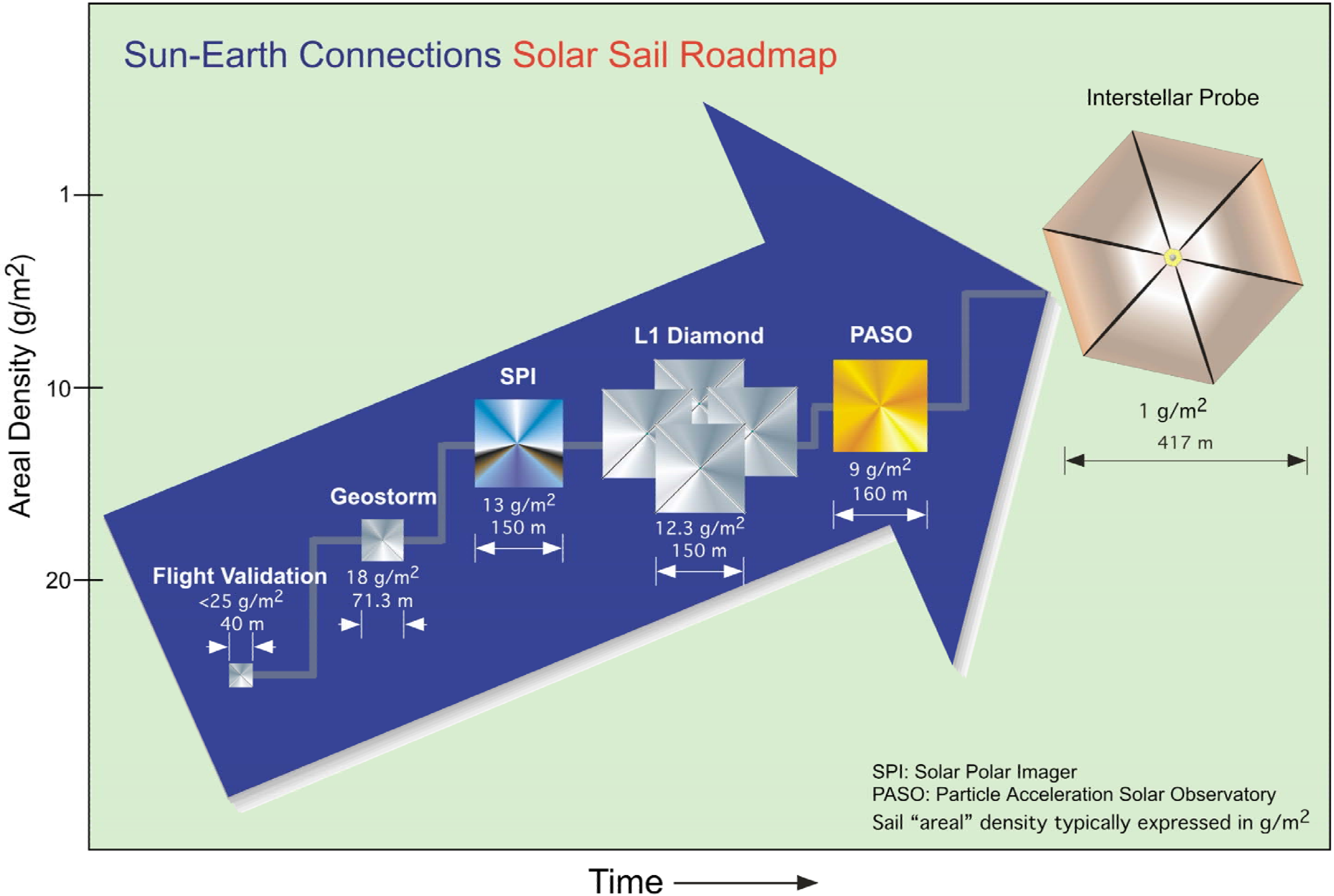
1. Lower the risk of solar sail technology as a primary propulsion system to a level enabling its selection for baseline on a NASA inner solar system science mission.

2. Solar sail propulsion demonstration and validation shall be scalable to inner solar system NASA missions

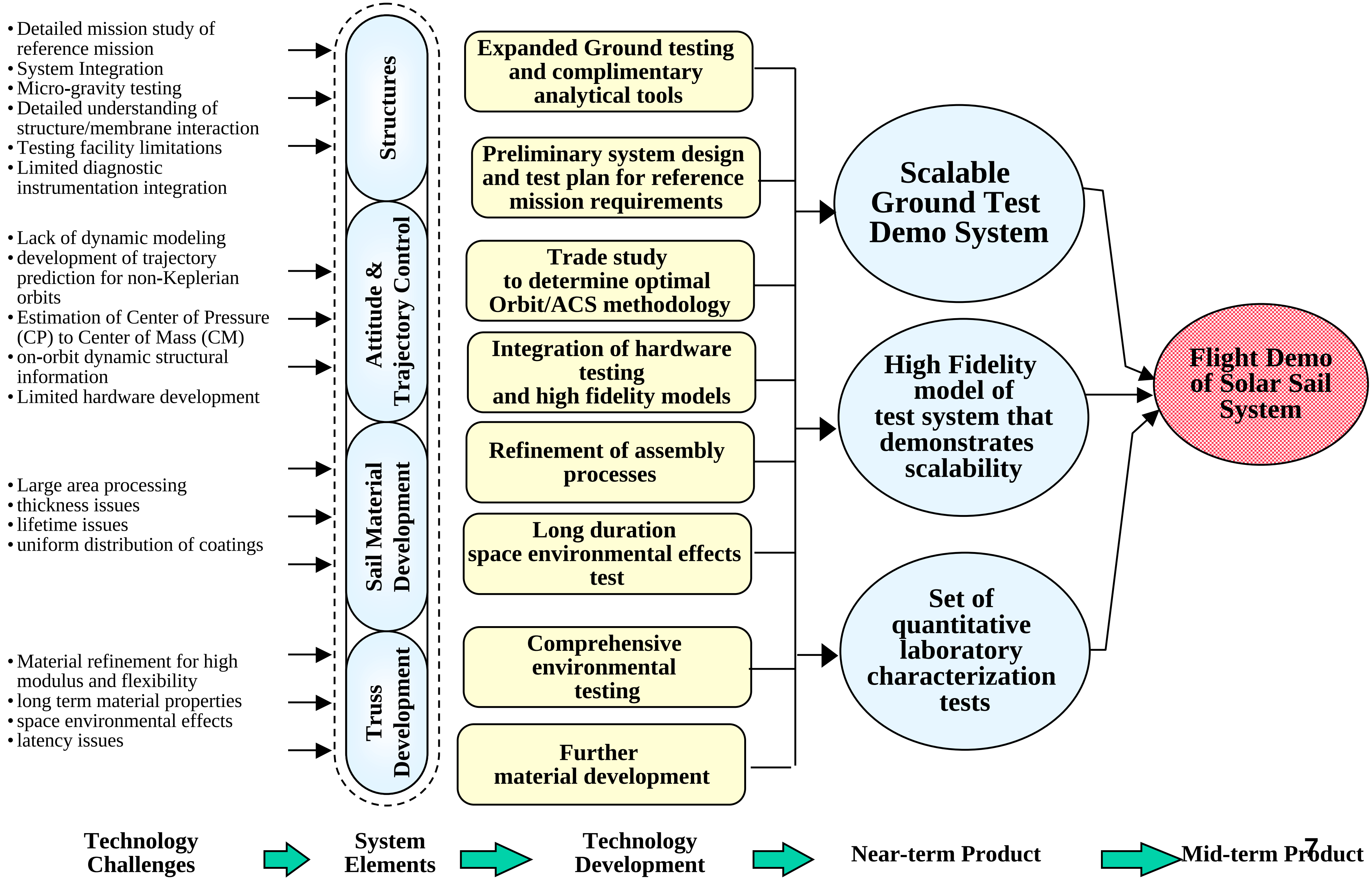
3. Attain closest approach to TRL 6 possible on the ground by the end of FY06

4. Maximize the potential for flight validation through partnerships and collaboration.

SSP Roadmap: Driven by Specific & Focused Mission Pull



Solar Sail Technology Assessment Group Roadmap
In-Space Propulsion Program



Sail Technology Classes

Mission Class	Timeline	SOA	Technology Challenges	NASA Mission Application
GEO/GTO Short Life	Past/Now	Encounter(?), Cosmos, ST-7, Znamya, Inflatable Antenna Exp	AO, radiation belts effects, high GG torques	None
1 Au	**Near Term**	**ISP Ground Demo,** ST-5 Geostorm ST-9 SSFV	**Validation in a space environment, Infusion into mission applications**	**L1 Diamond** **Solar Polar Imager (SPI)**
<0.25 Au	Mid-Term	Mission analysis, Future ISP work	Materials environments, Thrust vector range, Lightweight system, 100s m system scale size	Particle Acceleration Solar Observatory (PASO) Titan Explorer Saturn Ring Observer
Extra Solar	Far-Term	Mission concept analysis, Gossamer, Encounter(?)	Ultra-lightweight system Integrated system architecture Sub to kilometer system scale size	Interstellar Probe (ISP) Geospace System Response Imagers (GSRI) Outer Heliosphere Radio Imager (OHRI)

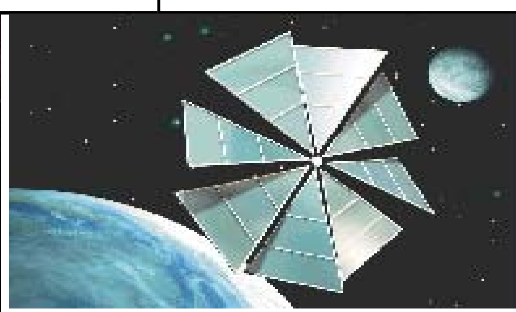
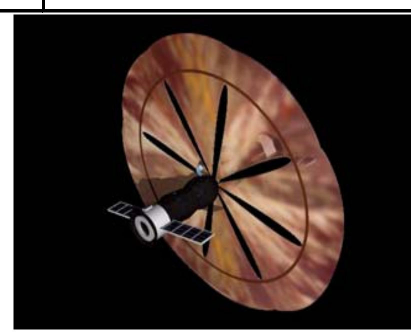
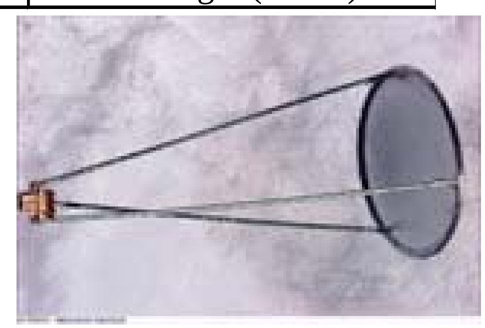


Photo courtesy of The Planetary Society

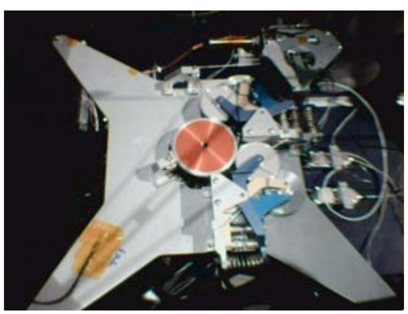


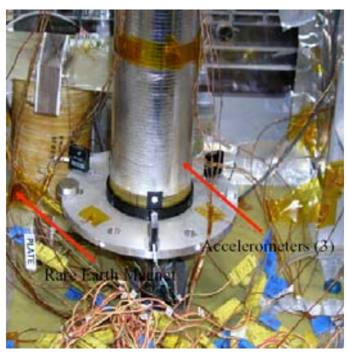


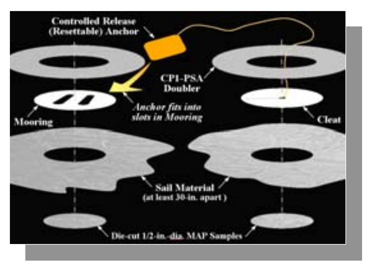
Solar Sail Propulsion Science Mission
Work Breakdown Structure

Solar Sail Propulsion Science Mission

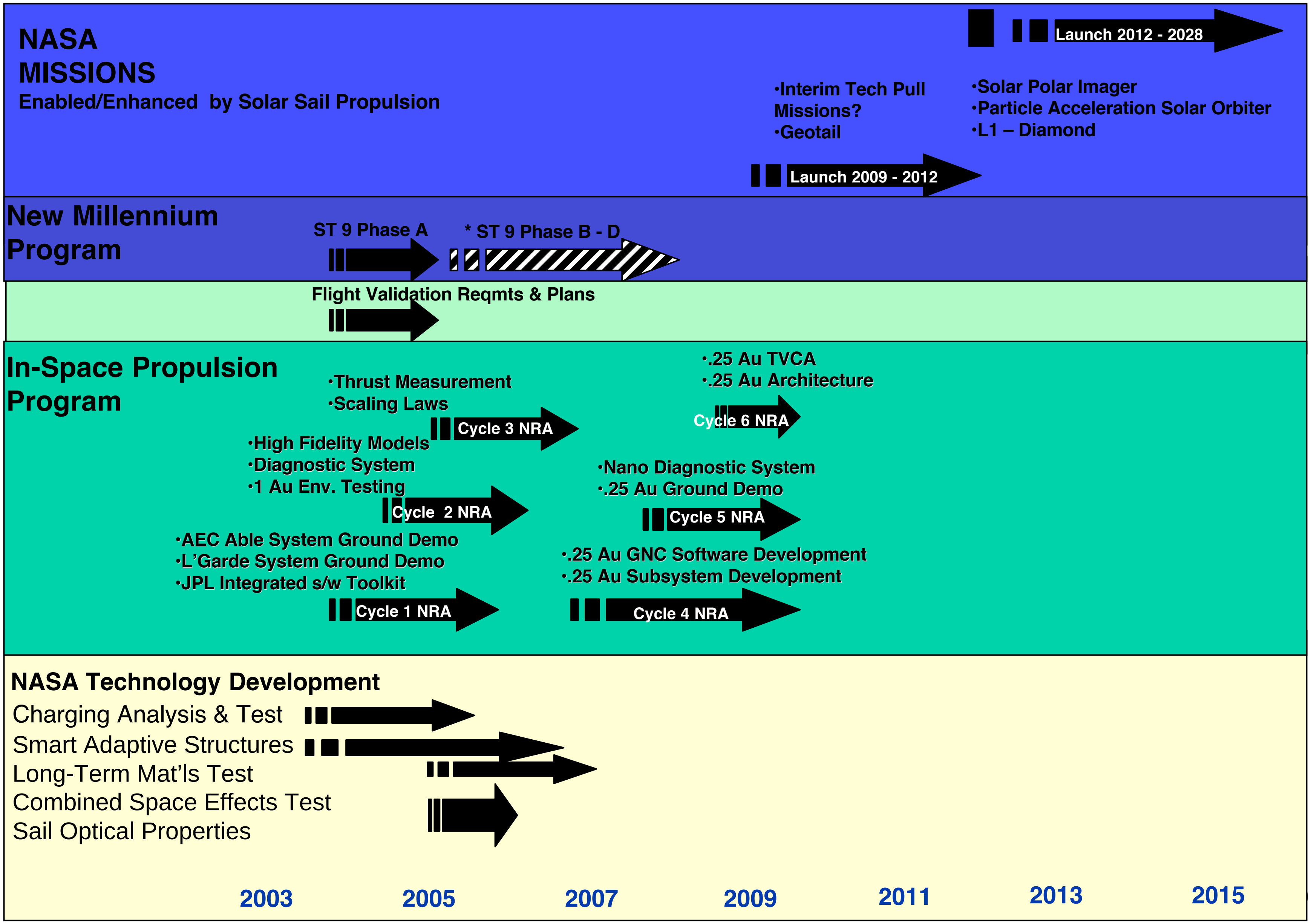
- **Management**
  - Mission Management
  - Resources Management
  - Schedule Management/ Planning
  - Mission Assurance
  - Configuration Management
  - External Reviews
  - Travel
  - Contract and Procurement Management
  - Training
  - Logistics
  - Formulation
  - Technology Development
- **Science**
  - Science Oversight
  - PI Science Activities
  - Co-I Science Activities
  - Instrument Scientist Activities
  - Algorithm Development
- **Mission System Engineering**
  - Systems Engineering Management
  - Systems Design
  - Technical Evaluation
  - Software Systems Engineering
  - Systems Integration & Test
  - Contamination Control
- **Spacecraft**
  - Spacecraft Management
  - Spacecraft Systems Engineering
  - Spacecraft Electrical System
  - Spacecraft Mechanical System
  - Spacecraft Thermal Control
  - Spacecraft Integration, Test & Verification
  - Spacecraft GN&C
  - Spacecraft Performance Assurance
  - Spacecraft Flight Software (SFS)
  - Spacecraft Ground Software (SGS)
  - Spacecraft Launch Support
- **Payload**
  - Payload Management
  - Payload Systems Engineering
  - Payload Integration, Test and Verification
  - Payload Operations
  - Payload Performance Assurance
  - Instruments A……N
- **Solar Sail Propulsion System (SPS)**
  - SPS Management
  - SPS Systems Engineering
  - SPS Electrical System
  - SPS Mechanical System
  - SPS Thermal Control
  - Sail Deployment Subsystem
  - Sail ACS
  - SPS Integration, Test & Verification
  - SPS Operations
  - SPS Performance Assurance
  - Instrumentation
- **Ground Systems Development**
  - Management
  - Systems Engineering
  - Product Assurance
  - Quality Assurance
  - Integration, Test and Verification
  - Mission Operations Center
  - Science/Data Operations Center
  - Data Distribution and Archival
  - Ground Station
  - Communications Network
  - Flight Dynamics
  - Testbeds for Ground Systems
  - Test and FOT Training
  - Travel
- **Launch Vehicle**
  - Spacecraft to LV Interface Definition and Verification
  - Launch site field support
  - Launch Vehicle Acquisition
  - External Reviews
- **Operations**
  - Mission Operations
  - Science Operations
  - Ground Station
  - Communications
  - Flight Software Sustaining Engineering
  - Ground Software Sustaining Engineering
  - Operations Services
  - Travel
  - Training
- **Education and Public Outreach**







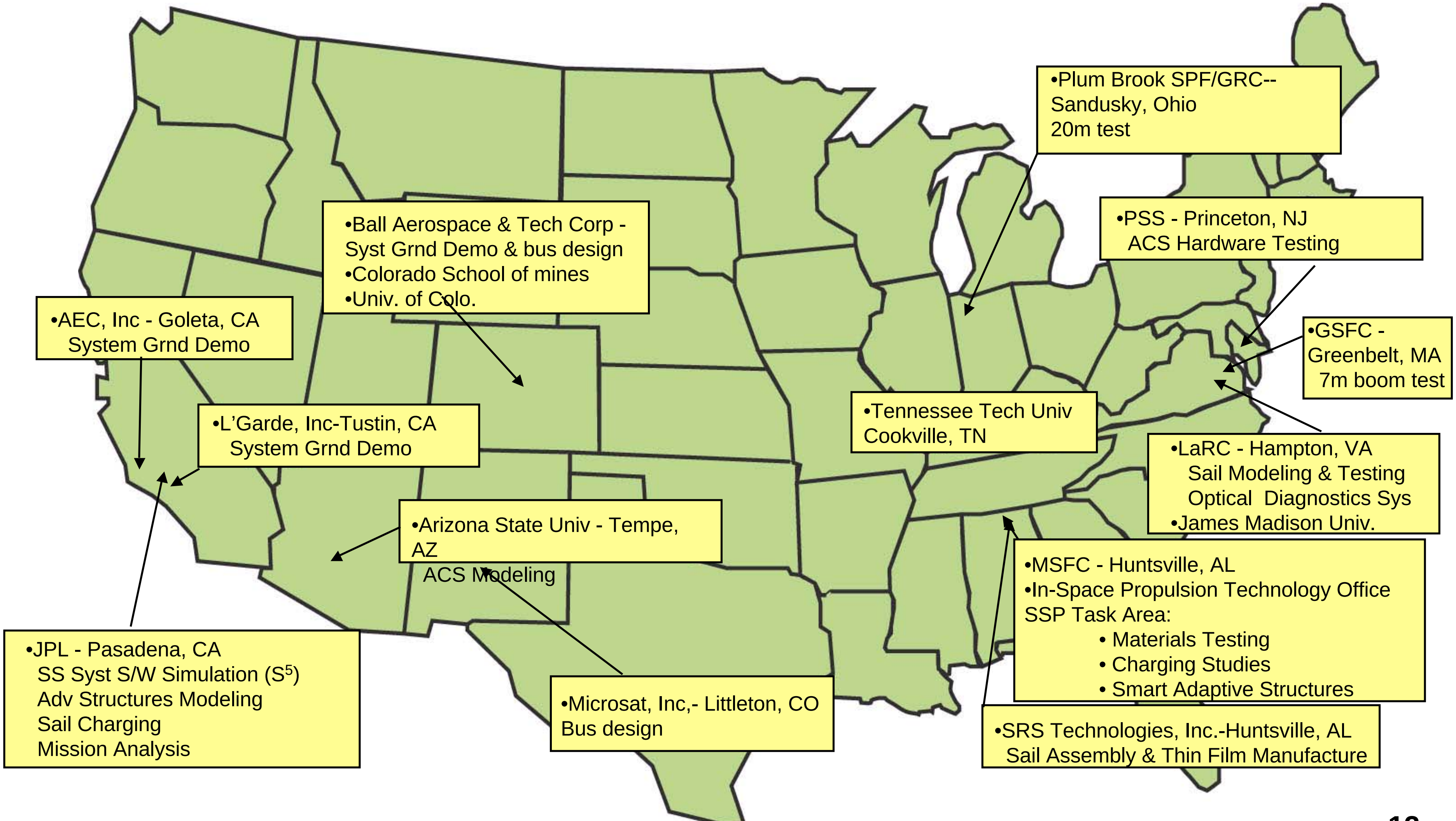
Solar Sail Propulsion Roadmap



SSP Tasks Funded to Date

- NRA Cycles 1 & 2
- Directed Tasks
- Systems Analysis Tasks
- Composite Schedule

Solar Sail Propulsion Participants



Funded Competed Work

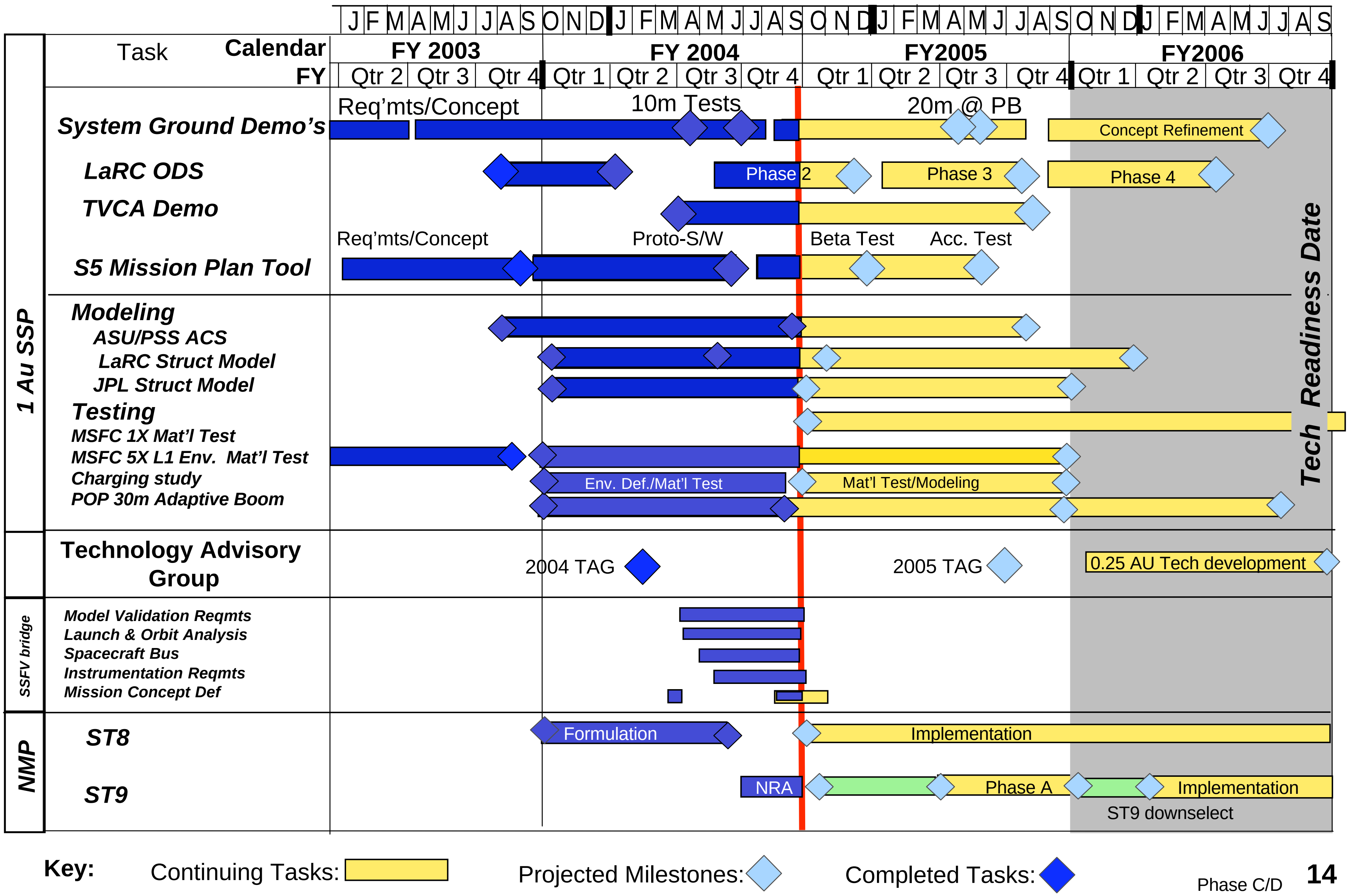
Cycle 1

Selection title	Prime
Scalable Solar Sail System Development and Ground Demonstration	**AEC**
Ground System Demonstrator	**L'Garde**
Solar Sails GN&C Tool Kit	**JPL**

Cycle 2

Selection title	Prime
Optical Diagnostics System for Solar Sails	**NASA LaRC**
Advanced Computational Models and Software for Design and Simulation of Solar Sails Including Experimental Validation	**NASA LaRC**
Development of a Low-Cost, Low-Mass, Low-Volume, and Low-Power Attitude Determination and Control System (L4-ADCS) and High-Fidelity Computational Models of Solar Sail Systems	**Arizona St Univ**
Laboratory Characterization of Candidate Solar Sail Material	**NASA MSFC**
Advanced Manufacturing Technologies for Solar Sails using Processes Developed Specifically for Production of Ultra-thin Solar Sail Materials for Near, Mid and Far Term Space Science Missions	**SRS Tech**
Structural Analysis & Synthesis Tools for Solar Sails	**NASA JPL**

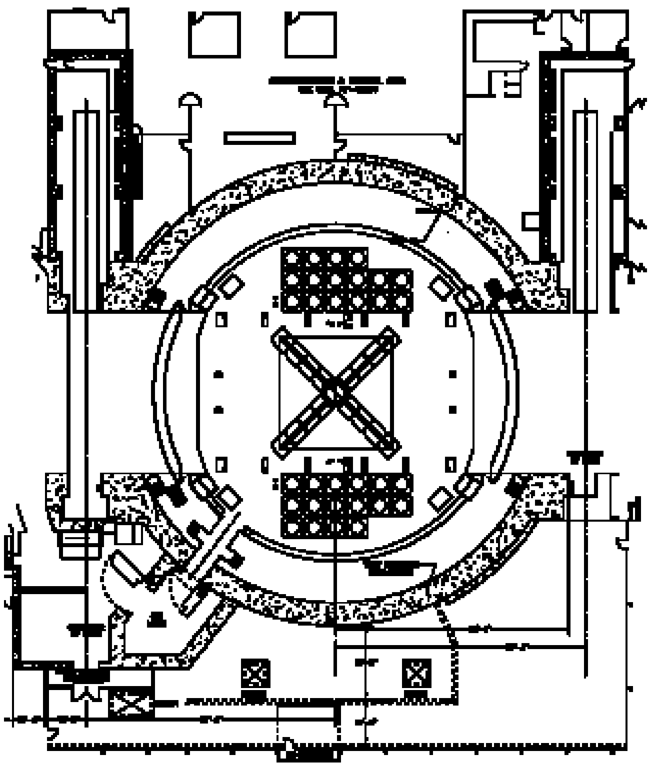
SOLAR SAIL PROPULSION
ISP & NMP ST9 Major Milestone

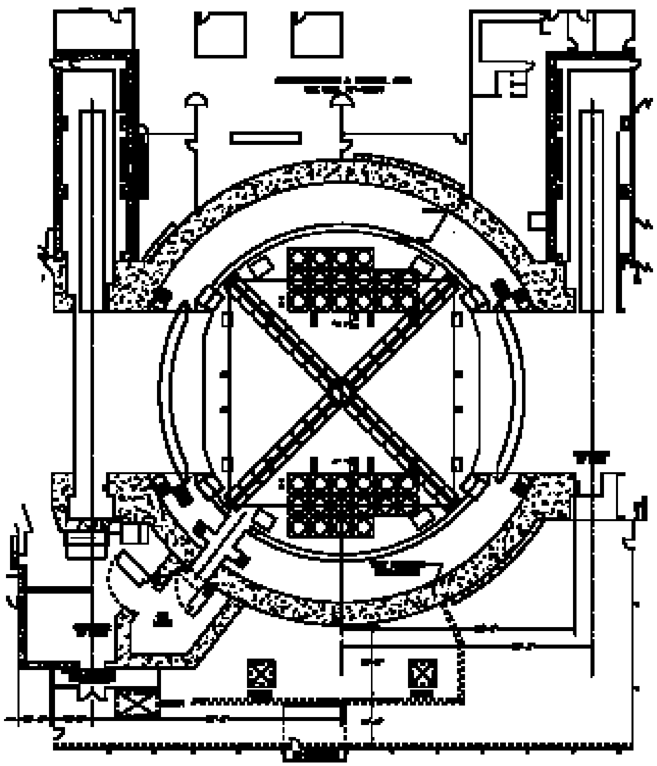


System Ground Demos: Plum Brook 10m & 20m Layouts

NASA Glenn Research Center, Plum Brook Station, Sandusky, Ohio

Test chamber: 30.5m (100ft) diameter by 37.2m (122ft) high





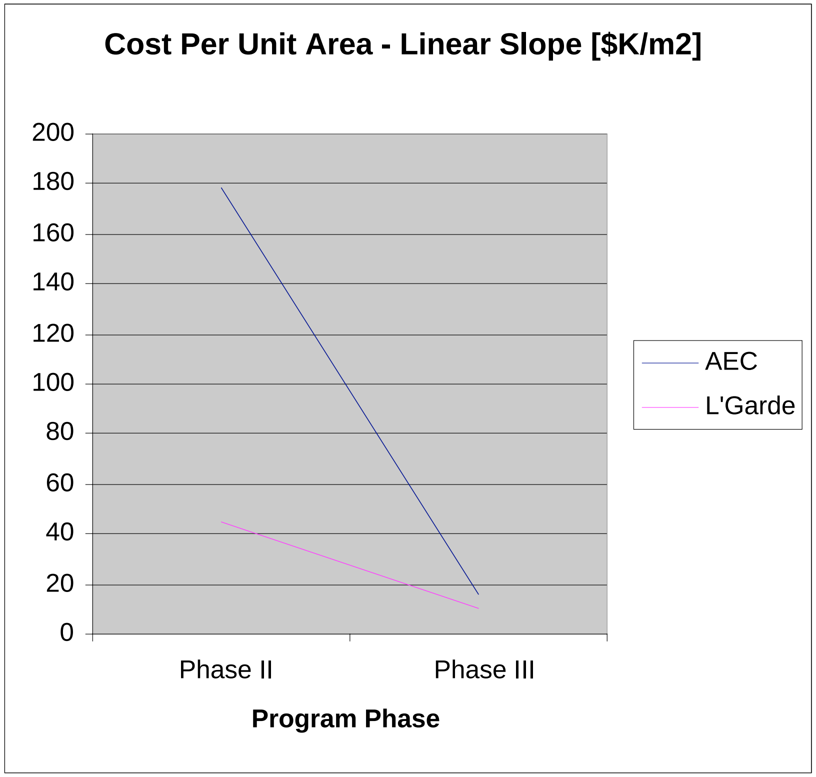
SGDs: 10 meter tests

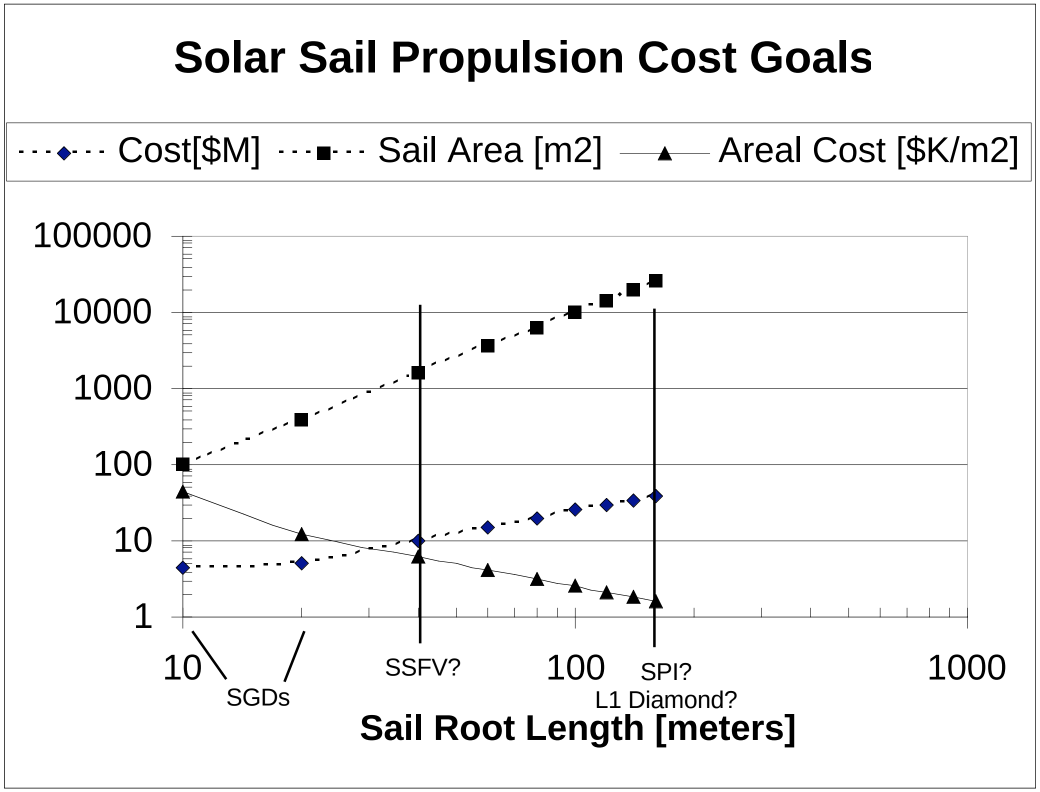
Project Office Level 1 Test Requirements	AEC		L'Garde	
Fabrication of scalable test article	No	Designs for 20m require features not necessary just for scaling. 20m booms require very different tip assy and deployment mechs. Sail will have ripstop and corner jumper, 10m did not. 5 micron sail was tested, 3 micron to be used. Patchwork fab/assy method to be used in phase 3 was not used in phase 2. Central structure to change significantly. Trolley needed for gravity offload.	No	Designs for 20m require features not necessary just for scaling. Some refinements from 10 meter design needed in mandrel, gravity off-load higher off ground, line management, manufacture process, addition of a control vane to one boom (cooling, offload, viewing. Etc.), offload structure (more support form above, higher off ground, smaller avialble footpring at end of beams, boom and sail assembly process. Wrong material in UV evaluation, thermal pipe height and length must change (and not impact test instrumentation)
Demonstrate transportation and handling of test articles and GSE	Yes	After transport from ABLE, test articles and GSE set-up & used at LaRC. No damage identified.	Yes	Some wear showed on a line due to vibrations rubbing Kevlar line during transport
Demonstration of scalable deployment	Part	Unexpected tear in sail in first ambient deployment attributed to sequencer. Border cord might have prevented further propagation of damage that would have affected propulsion performance or structural integrity, but test was stopped and fixed by human intervention. Later deployment was successful	Part	Runaway boom segment inflation and QC failure in packing lines caused half meter tear and several line failures, but not mission critical. Deployment not stopped and did continue to completion without human intervention. No successful repeat possible.
Acquire adequate measurements for the verification of computational models from test data	Yes	Measured gravity sag ~30% smaller than predicted. Although, the third mode shape could not be excited and a slight tweak of model to distribute spreader bar mass was required, multiple modeling results showed unusual high degree of comparison between prediction and test for deflections and mode shapes. Further analysis would be valuable.	Part	Boom tip cap gauges, accelerometers, videogrammetry failed. Low fidelity static deflection data from photogramemtry and dynamic data from laser vibrometer. Measured gravity sag ~30% smaller than predicted. Insufficient analysis of test data. Model frequencies close to prediction.
Mechanical assy drawings and electrical system schematic drawing for the test article and GSE	Part	Drawings made "available", but only partial set uploaded to sTIN. No drawing tree provided.	N	Drawings made "available", but none delivered to STIN. No drawing tree provided.

Technology Cost Extrapolation

Current History – Phase II costs indicate 1 vs 4 quadrant 10 meter demonstrators

Areal Costs must continue to reduce to keep total cost for science missions affordable

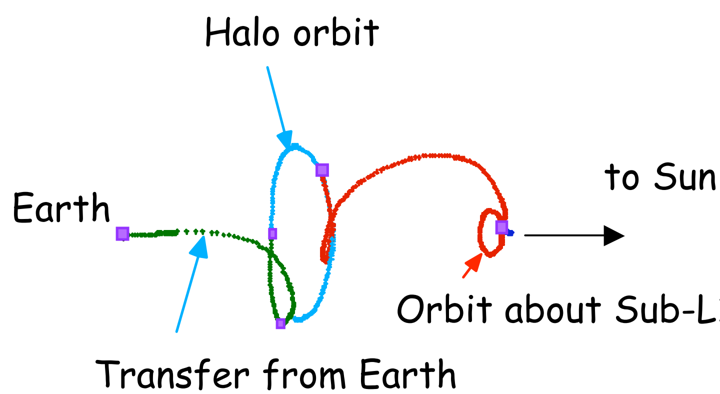




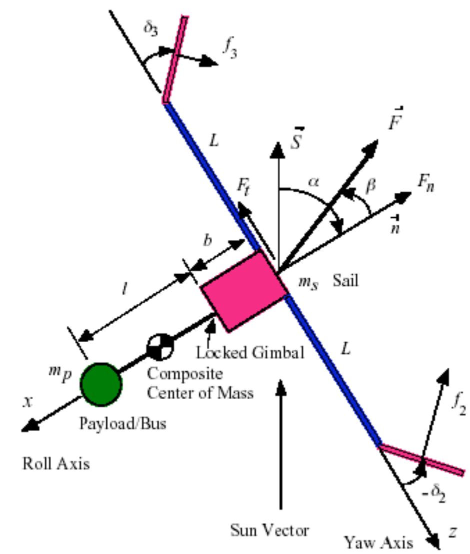
Note: Cost history is relevant to ISP-SSP system ground demonstrators

Solar Sail GN&C Challenges

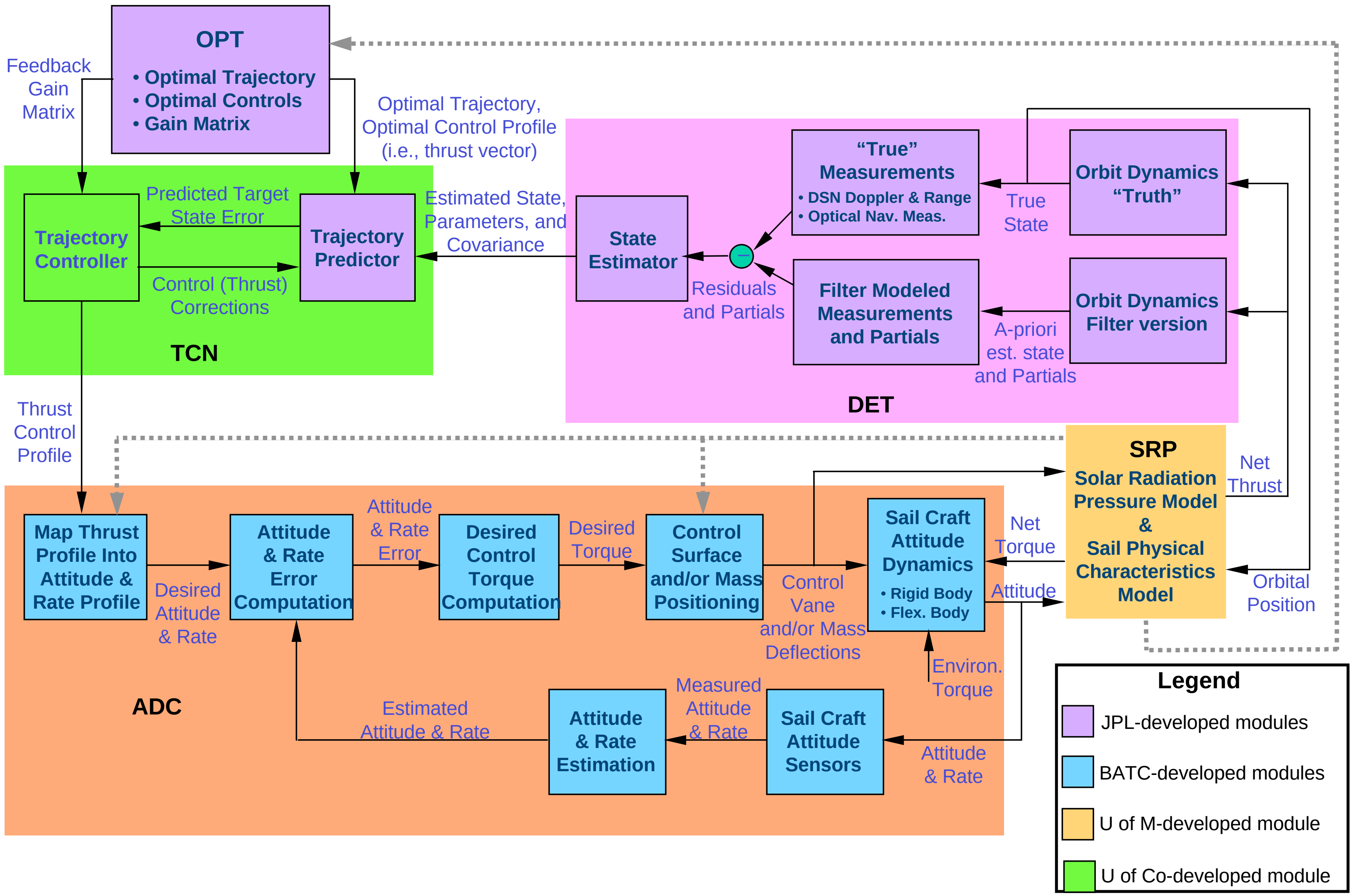
- Low Thrust Trajectories
  - Optimal Control Theory
  - Solar Sails Unique
  - Thrust Vector Constraint



- Attitude Control Systems
  - Optical
  - CP/CM
  - Conventional



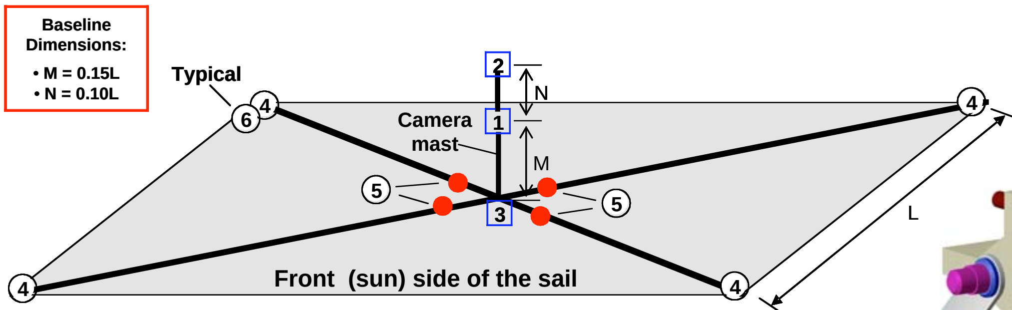
S5 GN&C Functional Architecture



Optical Diagnostic System Task Summary

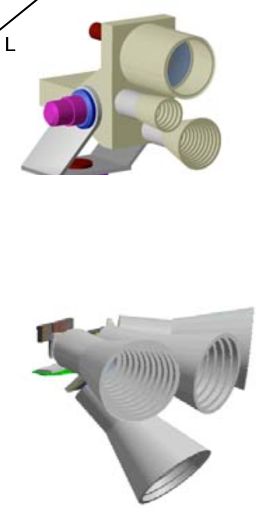
- Award for **Cycle 2 Topic: Integrated Solar Sail Diagnostics Package development**

- **PI: Richard Pappa, LaRC**
  - Ecliptic Enterprises Corporation (Pasadena, CA) – data and space requirements
  - South Dakota School of Mines – structural models and analysis
  - Texas A & M University – Image processing techniques
  - James Madison University – Infrared thermography and fiber optic sensors
  - AEC – System Ground Demo Integration
  - L'Garde System Ground Demo Integration



1 4 front-side 90-deg FOV camera clusters (16 cameras)
2 1 front-side inspection camera cluster with pan-tilt (3 c
3 4 cameras at hub, one looking down each boom (4 can
4 3 accelerometers at each boom tip (x & y bending, tors
5 Boom root strain sensors
6 Membrane tension sensors

Also:
- **Infrared thermography cameras on back side mast?**
- **Piezoelectric actuators for dynamic excitation?**



Sail and Boom Cameras: The Cluster Concept

TRL 6 Definition

- Origins
- Current Approach
- Potential Impacts

TRL 6: <u>Demonstration</u> of a <u>system</u> in a <u>relevant environment</u> (ground or space)

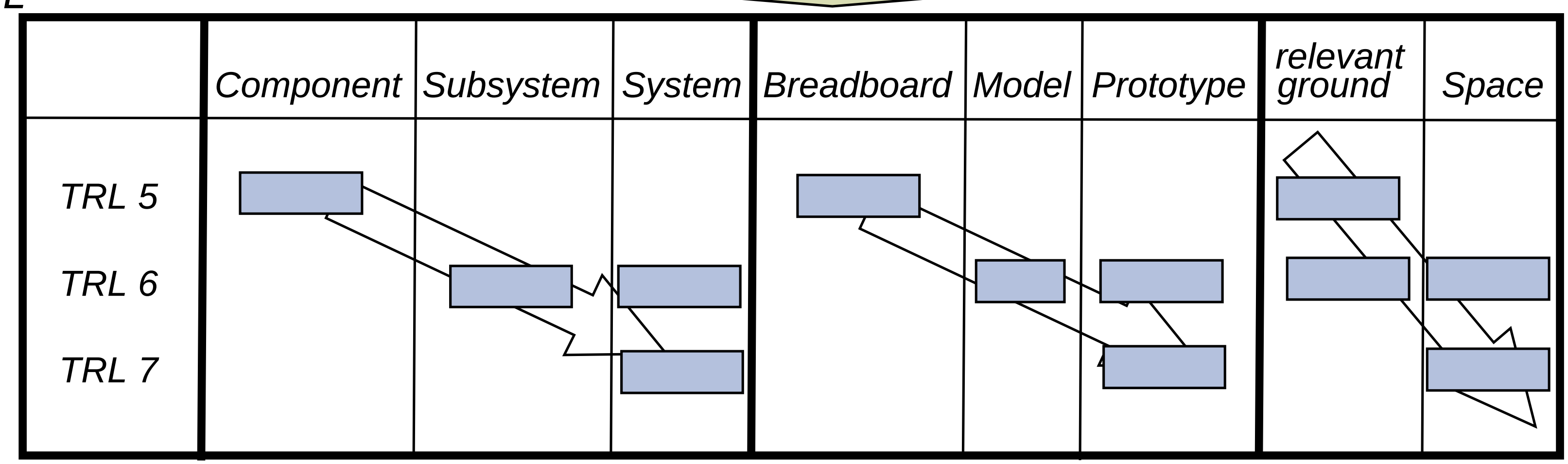
What is the Distinction?

TRL 5: *Component and/or breadboard validated in a relevant environment*

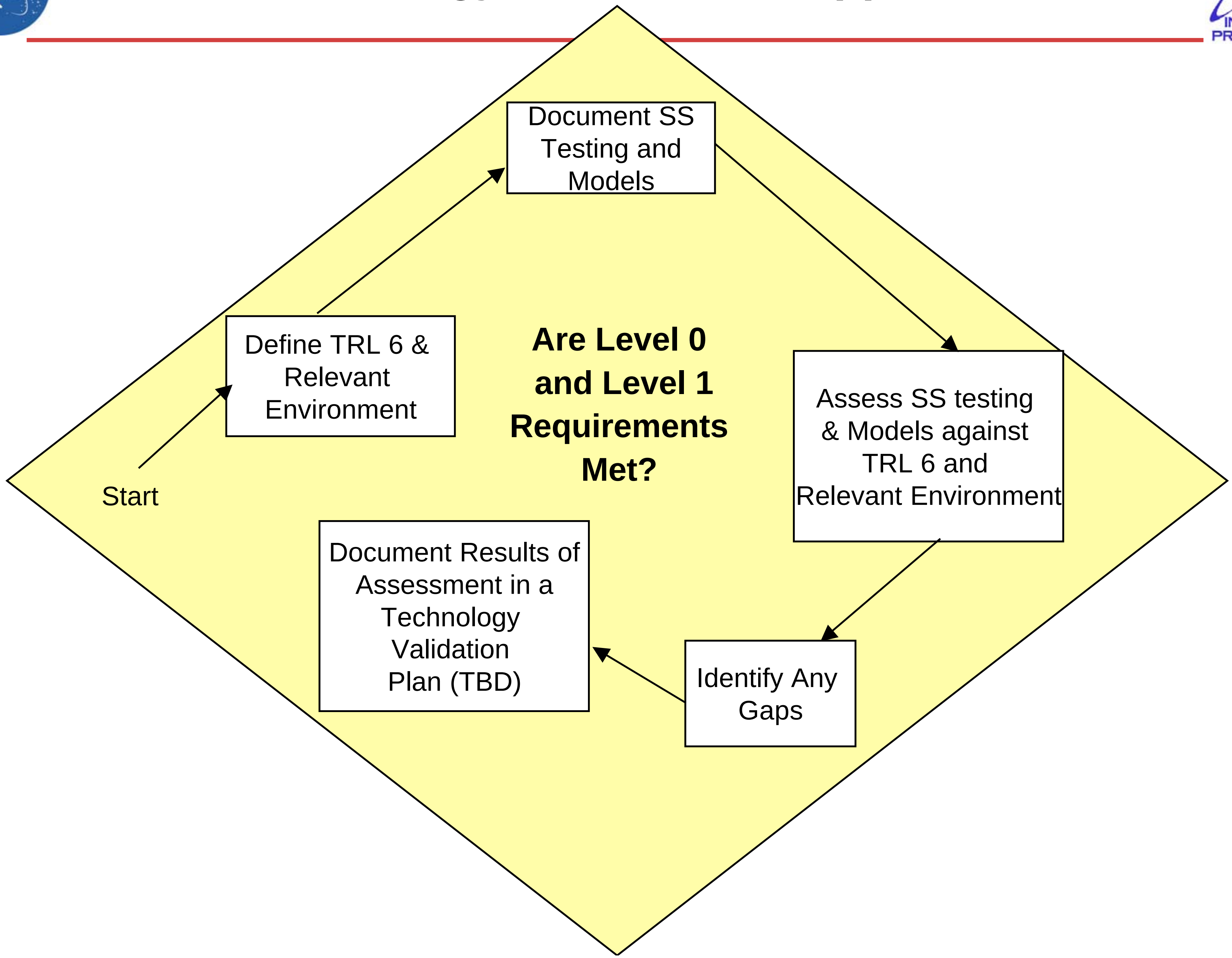
TRL 6: *System/subsystem model or prototype demonstration in a relevant environment on the ground or in space*.

TRL 7: *System prototype demonstrated in a space environment~*

	Subject	*Action*	*Condition*
TRL 5	*Component and/or breadboard*	*validated*	*a relevant environment*
TRL 6	*System/subsystem model or prototype*	*demonstration*	*a relevant environment on on the ground or in space*.
TRL 7	*System prototype*	*demonstrated*	*a space environment*



Technology Assessment Approach



Future Plans

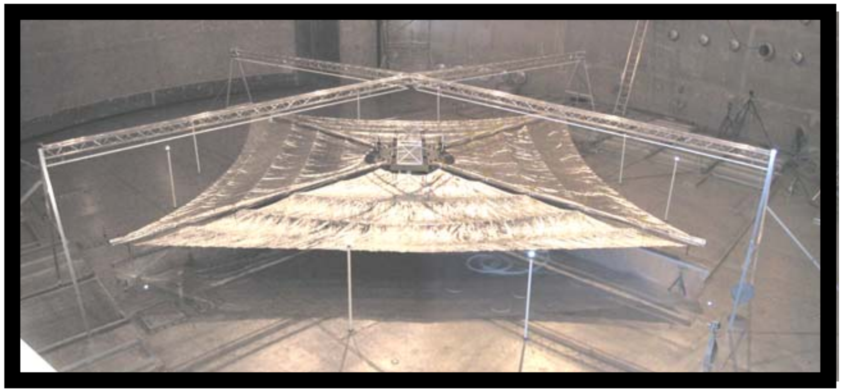
- **Tech Development**
  - NRA Cycles 3a &4
  - FY05 Directed Tasks
  - Systems Analysis
- **Flight Validation**
  - NMP – ST9
- **Science Mission**
  - SPI
  - L1 Diamond
  - Interstellar Probe
  - ??

- **ROSS NRA Cycle 3a**
  - Thrust Measurement
  - Scaling Laws
- **ROSS NRA Cycle 4**
  - TRL 6 Gaps
- **FY05 Directed Tasks**
  - Image Rendering for photogrammetry
  - Combined Env. Effects
  - Long Duration Matl'd Tetst
- **Systems Analysis**
  - SPI Vision Mission Study
  - L1 Diamond
  - PASO

SSP Near Term Challenges

- SSP demonstrations in simulated environments on the ground evolve concepts & capabilities well, but fall short of retiring risk for science roadmap mission applications.
  - full systems too large for conventional test methods/facilities
  - relevant environments ($<10^{-12}$g, 4K, 10^{-6}Torr) available only in space
  - full system thermal vacuum ground tests are a significant investment.

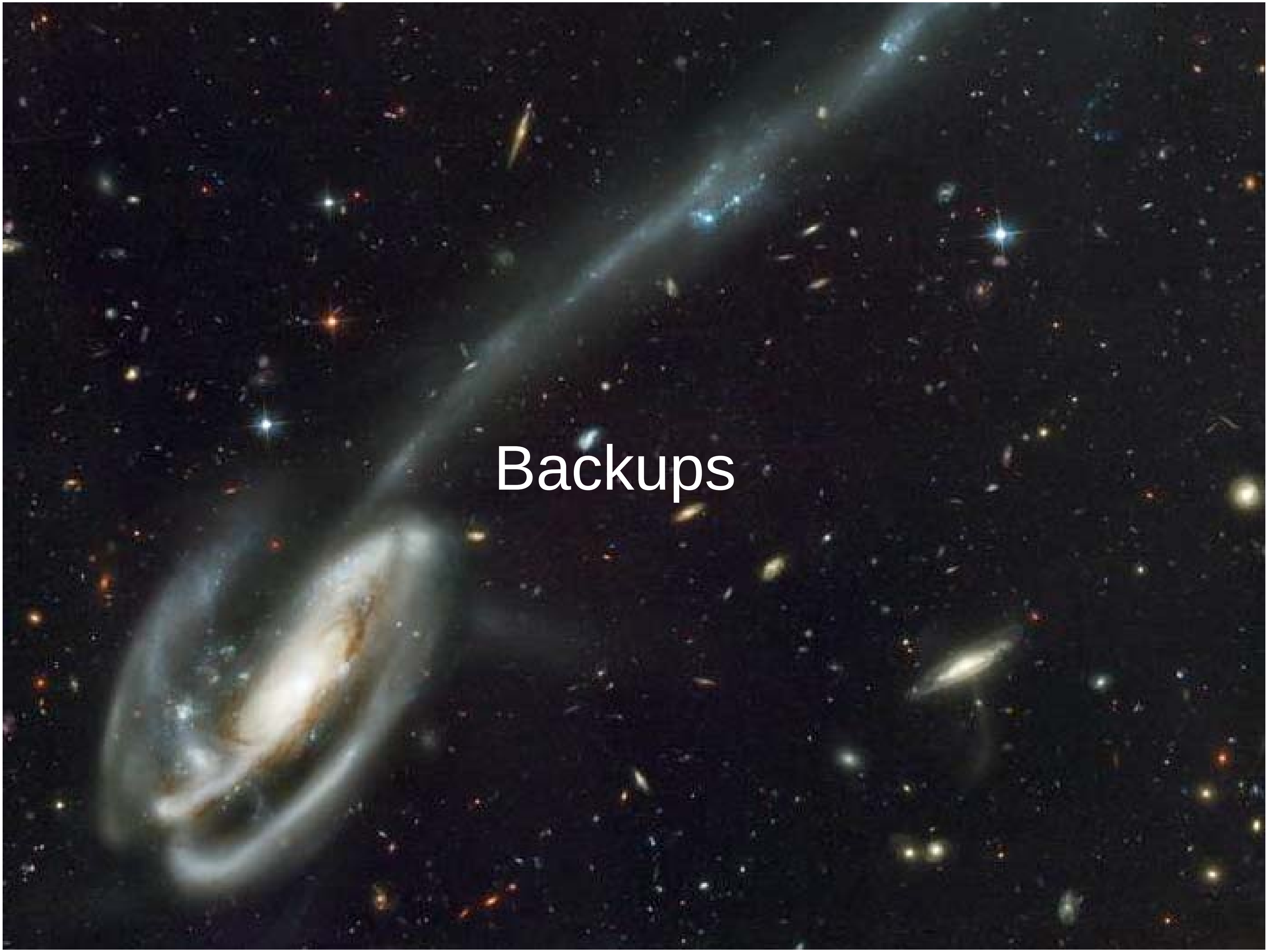
- Current SOTA is maturing rapidly
  - Mechanism designs evolving
  - Fabrication methods evolving
  - Integration with spacecraft(bus) & LV needs continued attention
  - Materials testing and charging studies so far have identified no showstoppers. Design specific issues TBD.
  - System dynamics simulation & analysis beginning
  - S5 useful immediately for trajectory design – unexpected optimization may redefine sail design reqmts.
  - Few unique component types – flight qual at assemblies/subsystem levels



Solar Sail Talking Points

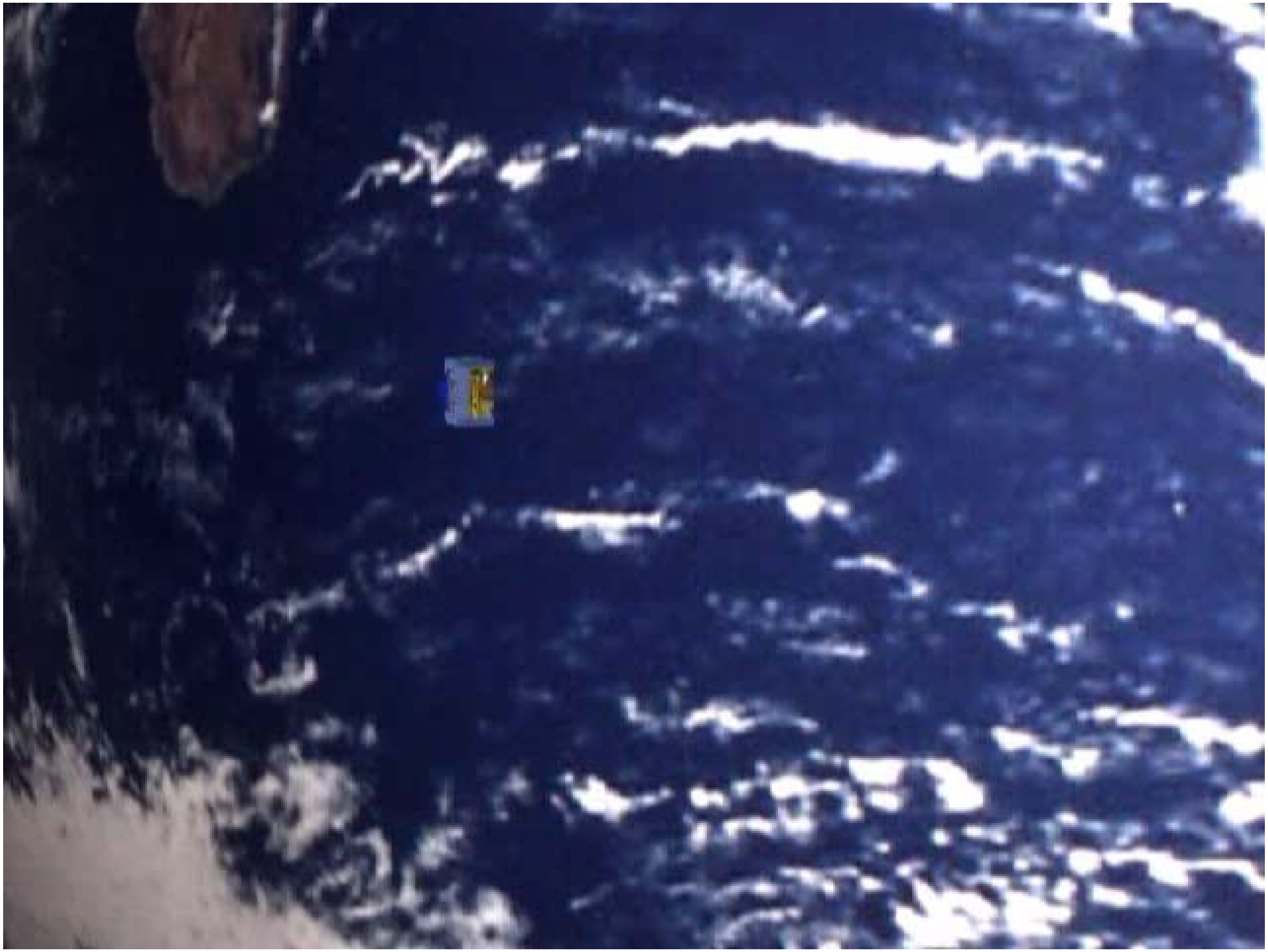
- **There are missions only solar sails can do--because you can't load up enough chemical propellant to do them conventionally.**
- **Solar Sails are environmentally friendly, safe,--and no toxic fuels or combustion byproducts, no high temperatures, or electrical currents, relatively small in size and weight.**
- **There is no doubt it will work--propulsion from sunlight saved a Mariner mission to Venus several decades ago. Recent advances in thin films, composites, and our understanding of how to engineer gossamer structures have made it even more practical and higher performing.**
- **No super-lasers or acres of unobtainium needed!**
  - Sails large enough to carry people or go to destinations beyond our solar system are still in the future.
  - But there is a current need for science probes and instruments that can be done in the next very few years almost within the current SOTA.
- **Solar Sail Propulsion (SSP) is the In-Space Propulsion technology activity with a goal of preparing a revolutionary alternative propulsion system for inner soilar system science missions through a program of ground development/demonstration then flight validation.**
- **Sails for radiation hazard sensing and communications platforms may be benefiicial to new agency initiatives**

Backups



How SSP Develops Content

- **Technology Assessment Groups (TAG)**
  - Objectives
    - To allow technologists and system experts an opportunity to participate in an open forum to exchange information, express ideas, and provide technical insight to those responsible for developing the In-Space Propulsion technologies
    - To identify and address challenges and issues that must be overcome in order to satisfy performance, schedule and system goals to advance the technology
    - To create a technology based roadmap which captures the expertise and recommendations of the TAG participants for consideration into the project management roadmaps
  - Approach
    - Identify the system/subsystem level components
    - Examine and determine the technology readiness level (TRL) of the current state-of-the-art technology of each subsystem
      - Access to Technical Papers and Conference Proceedings
      - Availability of unpublished test results from reputable sources
      - Participants' insight into and/or direct involvement with related research, systems analysis, and testing
    - Assess the level of difficulty to advance the technology
      - Identify technology challenges (gaps)
      - Identify potential gap fillers
- **Develop Roadmap/Investment Plan and Monitor**
  - TAM & LSE develop/revise roadmap based on
    - Program Leadership Guidance (based on budget, Tech Prioritization, executive decisions)
    - Budget changes
    - Technology maturation
    - TAG inputs
  - Reviewed monthly in HQ/FPR and MSFC/PMMR processes
  - Reviewed annually in POP exercises
  - Presented in Outreach Presentations (NOAA, Planetary Society, Workshops, Conferences)



Solar Sail Propulsion
Internal Management Structure

- **Edward Montgomery** (TD05)
  Technology Area Manager
  Solar Sail Propulsion
  - **Greg Garbe** (TD05)
    Solar Sail Flt Validation
    & Mission Outreach
    - NMP ST9
    - SPI Vision Mission Study
  - **Roy Young** (SD20)
    Lead Systems Engineer
    - DRDs
    - TAGs
    - Formal Reviews
  - **Joan Presson** (TD05)
    Assistant TAM
    - Budget
    - Schedule
    - Directed Tasks
    - Code U Interface
    - SBIR/STTR Interface
  - **Donna Patterson** (Sverdrup)
    Budget Analyst
    - Budget Analysis
    - Status Reports
    - Funds Control
  - **Tammie Sallo** (Gray R.)
    Project Analyst
    - Monthly Status Rqmts
    - Documentation Control
    - Facilitator of Formal Meetings & Reviews
    - STIN Management
  - **Roy Young** (SD20), COTR
    David Vaughan (JPL)
    Charlie Adams**,** Sys Eng (Gray R.)
    L'Garde GSD Contract
    - LaRC
    - JPL
    - MSFC
    - GSFC
    - GRC- Plum Brook
  - **Al English** (SD20), COTR
    David Vaughan (JPL)
    Charlie Adams, Sys Eng (Gray R.)
    AEC GSD Contract
    - LaRC
    - Ltwt Attitude Control Sys, ASU
    - MSFC
    - Adv Mfg Technologies, SRS
    - GRC-Solar Thermal & Plum Brook
  - **John Rakoczy** (SD71)
    ODS
  - **Andy Heaton**
    S5 Mission Sim Tools
  - **Joan Presson** (TD05)
    Materials Research
    - Modeling & Exp Validation of SS Charging, MSFC & JPL
    - Life Test of SS Material in Simulated Space, MSFC
    - Combined Space Environmental Effects, GRC & MSFC
    - Optical Properties, MSFC & GRC
    - Char of Material Including Sail Joining & Repair
  - **John Lassiter** (ED27)
    Structures
    - Advanced Computational Methods, LaRC
    - Structural Analysis & Synthesis Tools, JPL & MSFC
    - Smart Adaptive Structures, MSFC